

# Cosmic Ray Astronomy

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## **Abstract.**

Cosmic ray astronomy attempts to identify and study the sources of ultrahigh energy cosmic rays. It is unique in its reliance on *charged* particles as the information carriers. While no discrete source of ultrahigh energy cosmic rays has been identified so far, a new generation of detectors is acquiring the huge exposure that is needed at the highest energies, where deflection by magnetic fields is minimized and the background from distant sources is eliminated by pion photoproduction. In this paper, we summarize the status of cosmic ray astronomy, describing the detectors and the analysis techniques.

## 1. Introduction

The goal of cosmic ray observatories is to discover the sources of the Universe's highest energy particles, then to use cosmic rays to study the properties of these sources and of the magnetic fields that the cosmic rays have traversed. Individual cosmic ray particles have been observed to have energies as great as 50 Joules, and the mystery of how they are produced has persisted for 45 years [1]. Evidence now indicates that they are accelerated by electromagnetic processes, not produced by the decay of supermassive particles (see Sec. 5.1). While the energy spectrum and chemical composition of the cosmic rays are potential clues to the astrophysical accelerators, positive identification of the sources can only be achieved by using anisotropy of their arrival directions to reveal where the sources are.

Cosmic ray astronomy differs from electromagnetic, neutrino, and gravitational wave astronomy due to the electric charge of the messengers and is sometimes called charged particle astronomy. All other astronomy relies on neutral particle messengers.

Although there is no guarantee that discrete sources will be observable with cosmic rays, there are certainly reasons to be optimistic. The Larmor radius  $R_L$  for a particle of energy  $E$  and charge  $Z$  in a magnetic field  $B$  is roughly

$$R_L \simeq 1 \text{ kpc} \frac{E [\text{EeV}]}{Z B [\mu\text{G}]} . \quad (1)$$

For cosmic ray particles above several EeV (1 EeV=10<sup>18</sup> eV), the Larmor radius exceeds galactic dimensions for typical magnetic fields of  $\mu\text{G}$  strength. The highest energy cosmic rays could have sufficient magnetic rigidity to maintain their direction to better than a few degrees while traveling through the Galaxy, assuming they are protons. With sufficient exposure, the arrival directions from a strong nearby source should stand out as a high-density cluster on the sky. Moreover, above approximately  $6 \times 10^{19}$  eV, there should be essentially no background, because the cosmic background radiation removes such energetic particles before they can travel as much as 100 Mpc. Protons lose their energy to pion photoproduction; nuclei photodisintegrate; and gamma rays succumb to  $e^\pm$  pair creation. With the isotropic background from more distant parts of the Universe eliminated, only the foreground sources contribute.

The onset of pion photoproduction from the interaction of protons with the microwave background radiation at  $6 \times 10^{19}$  eV is expected to lead to a suppression of the cosmic ray flux above this threshold energy. Observational evidence for this so-called Greisen-Zatsepin-Kuz'min (GZK) suppression [2, 3] has been mounting in recent years after the Akeno Giant Air Shower Array (AGASA), with the largest cumulative exposure at that time, cast doubt upon it [4, 5]. The High Resolution Fly's Eye experiment [6] has claimed statistically significant evidence for the expected suppression of a power-law spectrum. The most recent spectrum from data taken with the Pierre Auger Observatory in Argentina is also consistent with the GZK suppression [7]. It appears that cosmic rays above the GZK energy threshold must originate in the nearby Universe, with source distances not exceeding 100 Mpc. Searches for the sources of cosmic rays can therefore

expect a background-free search for astrophysical objects within this “GZK-sphere” by selecting events above the GZK threshold energy. These super-GZK cosmic rays are at least a million times more energetic than any other messengers that have been detected from astrophysical sources.

The reward of measuring the cosmic rays from an individual source will not be limited to new knowledge about the astrophysical source itself. By studying how the arrival directions deviate from the source direction as a function of particle energy, it should be possible to infer valuable information about intervening magnetic fields that exist between the Earth and the source (see for example [8, 9, 10]).

The fact that no prominent source has so far been detected casts some doubt on this optimistic scenario. If there are indeed astrophysical sources of cosmic rays that can be identified by arrival directions, it is likely that the sources will first be detected collectively rather than individually. A class of sources can be identified statistically even if no single source is detectable.

Autocorrelation studies, for example, may reveal an excess of pairs and triplets of clustered arrival directions. Although any of the multiplets could occur by chance, an implausibly large number of them would constitute compelling evidence of discrete sources. But even without any multiplets of arrival directions, the sources of cosmic rays can be identified by a correlation of the (singlet) arrival directions with a class of candidate astrophysical objects. If the observed correlation were extremely unlikely to occur by chance from an isotropic cosmic ray intensity, then the correlation could be regarded as a special anisotropy consistent with the hypothesis that the class of astrophysical objects include sources of cosmic rays. This can happen even if the cosmic ray arrival directions show no clustering or large-scale pattern. Finding compelling autocorrelation of arrival directions or correlation of arrival directions with a class of astrophysical objects would validate the assumption that discrete sources exist and that the sources can be studied individually when sufficient cosmic ray exposure is obtained. From the Pierre Auger Observatory, there is now indeed evidence for a correlation between the arrival directions of ultrahigh energy cosmic rays and the positions of nearby Active Galactic Nuclei (AGN) [11, 12]. These results, described in Sec. 4.5, raise prospects of finally identifying individual sources with more data in the near future.

Information about the origins of cosmic rays should also be extractable from large-scale patterns in the celestial distribution of arrival directions. A cosmic ray gradient can be detected as a dipole. A quadrupole pattern may be expected if sources lie near some plane in space. Large-scale patterns may be the best handle on cosmic ray origins if they are not produced by discrete sources or if the discrete sources cannot be resolved. Large-scale patterns can be expected to be effective in the study of galactic production of cosmic rays near 1 EeV. Large observatories will obtain sky maps with high statistics in that energy regime. In order to exploit the power of spherical harmonics for characterizing the anisotropy, it is important that observatories acquire good exposure to the entire celestial sphere by having sites in both the northern and southern hemispheres.

The search for discrete cosmic ray sources occurs at the highest energies, where

magnetic deflections should be small. The challenge of cosmic ray astronomy is the fact that the flux of particles is tiny at such high energy, so enormous exposure is needed. Of course a major uncertainty is the strength of the galactic and intergalactic magnetic fields. Estimates of the field strength vary widely. In [13], Dolag *et al.* model intergalactic magnetic fields with magneto-hydrodynamical simulation of cosmic structure formation, using the (few) existing measurements based on Faraday rotation near clusters as boundary conditions. The authors find that over large parts of the sky, the angular deflection for protons of energy  $4 \times 10^{19}$  eV should be of order  $1^\circ$  for propagation distances up to 500 Mpc, with larger deflections occurring in cluster regions. However, Sigl *et al.* estimate that deflections might be much larger [14].

The galactic magnetic field is better known, but here, too, large uncertainties remain (see [15] for a review of experimental methods and results). The galactic magnetic field has a regular and a random (turbulent) component which affect the trajectories of charged particles in different ways. Estimates of the strength of the *regular* component exist from optical and synchrotron polarization measurements [16] and Faraday rotation measures of pulsars [17]; with their different systematics, polarization measurements tend to overestimate the field strength, whereas rotation measures tend to underestimate it. The experimental results indicate that the magnitude of the regular field in our local neighborhood is of order 2 to  $4 \mu\text{G}$ . There is a lot of uncertainty on how the field falls off along the direction perpendicular to the disk and in the galactic halo, which will strongly affect cosmic ray trajectories. As a rough estimate, a cosmic ray proton of energy  $6 \times 10^{19}$  eV traveling through a regular galactic field of strength  $3 \mu\text{G}$  for 1 kpc is deflected by  $3^\circ$ . Simulations based on more extensive models of the structure of the field, including the field in the galactic halo, essentially give values for the deflection consistent with this rough estimate [8, 9, 10]. Being proportional to the charge of the cosmic ray particle, deflections are much larger for heavier nuclei.

Deflections in the *random* component of the galactic magnetic field have been estimated in [18]. While the magnitude of the field strengths of the random and the regular component are comparable, deflections by the random component are expected to be smaller, since the correlation length of the random fields is only about 50 to 150 pc. A path of 1 kpc length would experience multiple small deflections, with no systematic change in direction. The mean square deflection due to the random fields is estimated in [18] to be smaller than deflections due to the regular component by a factor ranging between 0.03 and 0.3.

There is substantial quantitative uncertainty about the magnetic smearing of point sources due to regular and random magnetic fields within the Galaxy as well as in intergalactic space. For energies near and above the GZK threshold, however, it is certainly possible that protons arriving from a point source could be concentrated within a circle less than a few degrees in radius. While not guaranteed, charged particle astronomy is a realistic possibility.

Discovering the sources of cosmic rays (at all energies) has been a motivating objective for very high energy gamma ray observatories and also for neutrino detectors.

Gamma ray astronomy now studies astrophysical objects in gamma rays with energies up to tens of TeV. These are currently the highest energy particles whose sources have been unambiguously identified. A number of galactic and extragalactic sources have been identified, and new sources are now discovered on a regular basis with telescopes in both hemispheres (see the article by J. Hinton in this Focus Issue). Above several tens of TeV, gamma ray astronomy faces a limit, as interactions with extragalactic photon fields, mainly the infrared and microwave backgrounds, severely restrict the distances over which gamma rays can travel unattenuated by  $\gamma\gamma \rightarrow e^+e^-$  pair production.

In many ways, neutrinos are the ideal messenger particles for astronomy at the highest energies. Like gamma rays, neutrinos travel undeflected by magnetic fields, but unlike gamma rays, they are not absorbed in radiation fields. Of course the small neutrino cross section, while ideal to reveal possible sources, has a downside. Neutrinos are not easily absorbed in detectors either, and the major challenge of neutrino astronomy is to build detectors that can achieve a decent detection rate of astrophysical neutrinos. That requires at least kilometer-scale detectors. No sources of astrophysical neutrinos have been identified so far except the supernova explosion SN1987A and the Sun, both detected via neutrinos in the MeV range.

In this Paper, we summarize the prospects of charged particle astronomy. After a section on the conditions for discrete source detection (Sec. 2), we will discuss cosmic ray detection techniques and describe several past, current, and planned experiments (Sec. 3). Section 4 reviews past claims for discoveries of cosmic ray sources and describes some of the analysis techniques applied in searches for sources. In Section 5, we review the current status of astronomy with ultrahigh energy gamma rays and neutrinos. A section on the importance of full-sky coverage for the future of cosmic ray astronomy (Sec. 6) and a summary (Sec. 7) conclude the paper.

## 2. Conditions for discrete source detection

From the measured cosmic ray spectrum, we know that the intensity of cosmic rays is minuscule (of order several  $10^{-3} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$ ) at and above the GZK threshold. Enormous exposure is necessary to acquire enough arrival directions to obtain statistically compelling evidence for individual discrete sources. The fact that none has been discovered so far means that a big increase in exposure will be needed. An exposure of  $10^5 \text{ km}^2 \text{ sr yr}$  would yield several hundred arrival directions, roughly an order of magnitude more than has been obtained with the greatest exposure so far. Still, there is no guarantee that cosmic rays are accelerated at isolated discrete sources. Even if they are, the sources may be too numerous and individually weak. They may be transient or burst sources. They may emit only in narrow jets.

Here we will examine the dependence on the mean separation  $R$  between sources, assuming all of the sources to be identical steady sources which emit cosmic rays in all directions with a luminosity  $Q$  (cosmic rays per unit time). It is straightforward to show that the nearest source is more detectable if the mean separation  $R$  is large. For a high

density of sources (small  $R$ ), detection is difficult because each source is then very weak.

The measured energy spectrum tells us the intensity  $I(> E)$  above any threshold energy. (This is the number of cosmic rays per unit area per unit solid angle per unit time.) Knowing the intensity is equivalent to knowing the density of cosmic rays  $\rho = \frac{4\pi}{c}I$ , where  $c$  is the speed of light and  $I$  stands for the integral intensity  $I(> E)$  above the energy threshold. This spatial density of cosmic rays must be given by  $Q$  times the density of sources ( $1/R^3$ ) times the time of accumulation  $T$ . For super-GZK particles with an attenuation range of 100 Mpc, for example, the accumulation time would be 100 Mpc/ $c$ , whereas it would be at least an order of magnitude greater below the GZK threshold. Equating the two expressions for the cosmic ray density gives the luminosity  $Q$  of each source:  $Q = 4\pi IR^3/(cT)$ . The luminosity  $Q \sim R^3$  means that the luminosity of each source must be very high if the mean distance  $R$  between sources is large. For a source at distance  $r$  from the Earth, the flux is  $Q/(4\pi r^2)$  or  $IR^3/(cTr^2)$ . (Here it is assumed that the distance  $r$  is small compared to  $cT$  so that the flux is not greatly attenuated by the GZK effect.) The nearest source to Earth is likely to be at a distance that is comparable to the mean spacing  $R$ . Using  $r \sim R$ , the flux is  $\sim IR/(cT)$ . That is, the expected flux from the nearest source increases in proportion to the mean separation  $R$ . Discrete sources are more likely to be detectable if the mean separation  $R$  is large (but not greater than the GZK attenuation length). Further analysis has been presented elsewhere [19] regarding the factors that govern the detectability of discrete sources of cosmic rays both above and below the GZK threshold.

### 3. Cosmic ray detectors

The primary cosmic ray flux is a steeply falling power law in energy, and the integrated flux above  $10^{19}$  eV is only about one particle per square kilometer per year. This rules out direct detection of the primary cosmic ray particle with satellite or balloon-borne detectors, as large areas are required to accumulate reasonable statistics. Consequently, cosmic ray detectors at ultrahigh energies use the Earth's atmosphere as the detector medium. The primary cosmic ray particles are not observed directly, since they interact in the upper atmosphere and induce extensive air showers with roughly  $10^{10}$  particles for a  $10^{19}$  eV primary. The properties of the original cosmic ray particle, such as arrival direction and energy, have to be inferred from the measured properties of the extensive air shower.

Two detector types have traditionally been used to record air showers: surface detector arrays and air fluorescence detectors. The former consist of arrays of particle detectors on the Earth's surface that sample the particles of the air shower cascade that reach the ground. The AGASA experiment in Japan is an example of a pure surface detector array. In its final configuration, AGASA comprised 110 scintillation counters separated by 1000 m and spread over an area of  $100 \text{ km}^2$ . The array took data between 1987 and 2003 and collected a total of 72 events with zenith angles smaller than  $45^\circ$  above  $4 \times 10^{19}$  eV. It achieved an angular resolution of  $2.5^\circ$  (68%) at energies above

$10^{19}$  eV.

Scintillation counters are not the only possible basic unit for surface detector arrays. The Haverah Park experiment, a  $12 \text{ km}^2$  air shower array operated in England between 1967 and 1987 [20], pioneered the use of water Cherenkov detectors. The particle detectors are light-tight water tanks with photomultiplier tubes inside. The tubes detect the Cherenkov radiation from air shower particles crossing the tanks.

Surface detector arrays sample the air shower at one altitude only and do not record the development of the shower in the atmosphere. The total energy of the air shower and thus the incident cosmic ray primary is connected to the measured particle density on the ground by air shower simulations, making the energy determination of cosmic rays with ground arrays model-dependent.

In contrast, the air fluorescence technique is able to image the shower development in the atmosphere. The measured fluorescence light is produced when particles of the extensive air shower interact with nitrogen molecules in the atmosphere. A nearly calorimetric energy measurement is obtained, because the fluorescence light produced is proportional to the energy dissipated in the atmosphere. With the air fluorescence technique, quantities like the height of the shower's maximum size can be determined directly. If the shower is viewed simultaneously by two detectors in stereo mode, the arrival direction can be reconstructed with an accuracy of less than  $1^\circ$ . The main shortcoming of the technique is the low duty cycle of only about 10 %, as air fluorescence detectors can only be operated on dark, moonless nights with good atmospheric conditions, when the small fluorescence signal can be distinguished from the night sky background.

An example of a pure air fluorescence detector, the High Resolution Fly's Eye (HiRes), operated between 1997 and 2003 on the Dugway Proving Grounds in Utah. With the completion of a second site, HiRes operated in stereo mode after 1999 and collected a total of 44 stereo events above  $4 \times 10^{19}$  eV, with an angular resolution of  $0.6^\circ$  (68 %) above  $10^{19}$  eV.

The measurements of cosmic ray air showers by ground arrays and air fluorescence detectors have fundamentally different systematic errors. Surface detector arrays depend on the numerical simulations of air showers, including hadronic interactions that occur at energies well above experimental verification. Air fluorescence measurements of air shower energies, on the other hand, are nearly calorimetric, and the largest contribution to the systematic error comes from what is presently a 15 % proportionality between air fluorescence and charged particle energy loss in the atmosphere. Moreover, atmospheric attenuation of the fluorescence light on its way to the detectors must be accurately known. Scattering of the fluorescence light by aerosol particles causes a variable amount of attenuation which must be monitored rigorously. The aerosols also affect the amount of forward Cherenkov light which is scattered to the detectors and collected together with the fluorescence light. Clouds are more obvious obstructions of fluorescence light that require continuous automated monitoring. In addition, absolute calibration of the fluorescence detectors (photon flux per analog-to-digital-converter(ADC)) is a challenge

since there is no naturally occurring calibrating flux. On the other hand, nature does provide an abundance of muons which allow continual calibration of the “vertical equivalent muon” signal level for a water Cherenkov surface detector. The individual surface detector stations are thereby automatically calibrated, but the measurement of air shower energy relies on air shower simulations. The fluorescence detector provides the air shower energy by a calorimetric method that is simple in principle, but determining the energy deposition from the detector signal is not at all simple in practice.

The two types of detection are complementary in other respects as well. The surface array operates continuously with an acceptance which is uniform over the array and which is independent of energy (above its full-efficiency threshold). In contrast, the fluorescence detector has an irregular duty cycle governed by weather, sun, and moon. Its aperture varies with time as atmospheric conditions change, and the aperture is always larger for higher energy showers which produce more light and so can be seen from a larger distance. On the other hand, the fluorescence detectors measure showers equally at all zenith angles, whereas the response of the surface detector depends on the shower inclination. Because of their different systematic errors, the two independent detection techniques are complementary, and the new generation of cosmic ray experiments uses *both* techniques at the same site to check the systematic errors in each of them and to obtain a maximum amount of information for the subset of showers that are recorded during clear dark nights.

The Pierre Auger Southern Observatory, currently nearing completion in Malargüe, Argentina, is the first modern *hybrid* cosmic ray experiment, and the first large cosmic ray experiment operating in the southern hemisphere. In its final stage, the surface detector array of the Pierre Auger Southern Observatory will comprise 1600 water Cherenkov detector tanks, deployed over an area of 3000 km<sup>2</sup> using a regular grid of triangles with 1500 m distance between nearest neighbors. Three photomultiplier tubes in each of the light-tight tanks measure the water Cherenkov light produced by the particles of the extensive air shower cascade that hit the tank. In addition, four fluorescence detector stations overlook the surface detector array from the periphery, each with a field of view of 180° in azimuth and covering an elevation angle range from 1.6° to 30.2° above the horizon. Using “hybrid events,” *i.e.* events seen both in the surface and the fluorescence detector, the observatory can calibrate the surface detector array without reference to air shower simulations. The calorimetric energy measurement of the fluorescence detector is found to be proportional to the water tank signal on the ground 1000 m from the core.

The Pierre Auger Observatory started scientific data taking in January 2004 and has published first physics results [11, 12, 21, 22, 23, 24]. With the surface detector alone, it achieves an angular resolution of 0.9° (68%) above 10<sup>19</sup> eV. With the fluorescence detector and at least one surface detector station, the angular resolution is about 0.6°.

The “hybrid” concept is also used by the Telescope Array (TA) experiment [25] currently under construction near Delta, Utah. Upon completion, the experiment will consist of 576 double-layer scintillation counters with 3 m<sup>2</sup> area each, deployed over



an area of  $1000 \text{ km}^2$  with  $1.2 \text{ km}$  spacing between the counters, and three fluorescence detectors overlooking the surface detector array, each covering  $108^\circ$  in azimuth and  $3^\circ - 31^\circ$  in elevation. For the surface detector array, an angular resolution of  $1.5^\circ$  is expected.

#### 4. Prior Hints for Cosmic Ray Sources

The small world data set of cosmic ray arrival directions of the pre-Augger era, consisting of little more than 100 events with energies above  $4 \times 10^{19} \text{ eV}$ , has been subjected to intense searches for anisotropies on all angular scales, including a variety of attempts to correlate classes of known astrophysical objects with cosmic ray arrival directions.

None of the earlier efforts to identify the sources from sparsely populated skymaps produced statistically convincing evidence for small-scale clustering or correlations with any class of objects, nor did they find a statistically convincing excess from any individual astrophysical object. “Statistically convincing” should be emphasized here, as there is actually no shortage of claims for clustering, correlation with classes of astrophysical objects, and excesses from plausible sources. Among the “signals” that have repeatedly been reported in recent years are (1) an excess of cosmic rays with energies around  $10^{18} \text{ eV}$  near the galactic center [26], (2) evidence for clustering of arrival directions of cosmic rays with energies above  $4 \times 10^{19} \text{ eV}$  on small angular scales ( $\simeq$  degrees) [27, 28, 29, 30, 31, 32], and (3) significant correlations with objects of the BL Lacertae class of AGN [34, 35, 36]. Most of the analyses leading to these claims were based on arrival directions recorded by AGASA, though they are not necessarily claims by the AGASA collaboration: the list of AGASA events above  $4 \times 10^{19} \text{ eV}$  is one of the published and openly accessible lists of cosmic ray events currently available. Whenever these claims have been subjected to tests with statistically independent data, they have failed. Much earlier there were suggestions of significant first and second harmonics in right ascension, suggestive of large-scale celestial anisotropy [37], and evidence for a flux from the direction of Cygnus X-3 was reported from two experiments [38, 39]. Recent experiments with much greater exposure and superior resolution have not confirmed any early indications of anisotropy.

We will now summarize and discuss several of the recent claims for significant deviations from isotropy and subsequent tests of them with new, statistically independent data. We also analyze what “went wrong” in the original analysis and what lessons can be learned for current and future searches for anisotropy and correlations with astrophysical sources.

##### 4.1. Galactic Center

One of the most promising reports of a possible discovery of a cosmic ray source is the announcement by the AGASA collaboration of a  $4\sigma$  excess of cosmic rays from the region of the galactic center [26]. The excess shows up in a very narrow energy

band, between 0.8 EeV and 3.2 EeV, while all neighboring energy bins show no excess. AGASA is located in the northern hemisphere and the galactic center at declination  $\delta = -28.9^\circ$  is not in its field of view, but lies just outside. The excess was found by integrating event densities over a  $20^\circ$  radius at each sky location. The significance of  $4\sigma$  should not be confused with a valid chance probability, since the energy band and the integration radius are *a posteriori*, chosen to optimize the signal after analyzing the data. No source flux is given in [26].

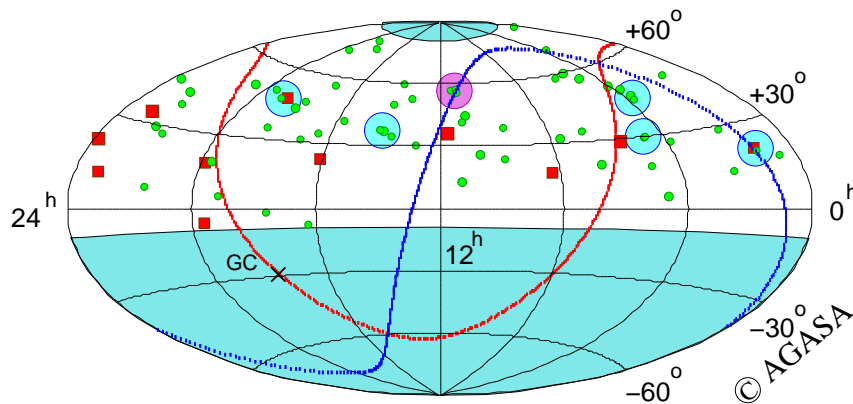
Interest in this possible source, however, remained high for two reasons. First, in an independent analysis of archival data taken between 1968 and 1979 by the SUGAR array in Australia [40], an excess near the galactic center was detected at the  $2.9\sigma$  level. The location of the excess did not coincide with AGASA’s location of maximum excess, but given the large integration circle of AGASA’s analysis and the angular resolution of SUGAR, both excesses could stem from the same source. Interestingly, the SUGAR excess is consistent with a point source. Given the presence of galactic magnetic fields, this implies neutral particles like neutrons and photons. However, since SUGAR measures the secondary muons of the air shower underground, photon primaries with their small muon content are unlikely candidates.

The second reason is related to theoretical expectations. The galactic center region is a natural site for cosmic ray acceleration. It contains a supermassive black hole, hosts a dense cluster of stars, stellar remnants, and the supernova remnant Sgr A East. In a striking coincidence, the decay length of neutrons of energy  $10^{18}$  eV is roughly 8.5 kpc, the distance between us and the galactic center. Neutron primaries would therefore offer an explanation for why the signal only shows up in such a narrow energy band: neutrons below  $10^{18}$  eV decay before reaching the Earth, and at energies higher than several  $10^{18}$  eV, the source runs out of steam. Furthermore, if the TeV gamma radiation recently observed by the CANGAROO II [41], H.E.S.S. [42], and Whipple [43] air Cherenkov telescopes is produced through photo-meson production with ambient photon fields, a flux of  $10^{18}$  eV neutrons is expected [44, 45, 46, 47, 48].

With its southern location, the Pierre Auger Observatory is in an excellent position to verify or rule out an excess of cosmic rays from the galactic center. A search for an excess from the galactic center using the first 2.3 years of data [22] was one of the first publications by the Pierre Auger experiment. With a data set already larger than AGASA’s data set by a factor of 3 and larger than the SUGAR data set by a factor of 10, the excess was not confirmed. The data were used to set a source flux upper limit that excludes several theoretical models of neutron production [44, 45] and the source flux given by SUGAR [40].

#### 4.2. Small-Scale Clustering

One way to try to identify the sources of ultrahigh energy cosmic rays is to search for deviations from isotropy in the data set itself rather than establishing matches with possible sources, i.e. to look for an “autocorrelation.” As an example, if cosmic ray



**Figure 1.** Skymap (in equatorial coordinates) of arrival directions of cosmic rays with energies above  $4 \times 10^{19}$  eV recorded by the AGASA experiment between 1990 and 2002. Events with energies above  $10^{20}$  eV are shown in red. Clusters are indicated as circles (blue for doublets, pink for the triplet). The galactic plane is indicated by the red line, the supergalactic plane by the blue line. Taken from [33].

arrival directions tend to “cluster” by showing more multiplets (doublets, triplets,...) of events than can be expected in a random isotropic data set of the same size and exposure, it could indicate that cosmic rays originate in nearby, discrete sources. Attempts to find small-scale clustering of ultrahigh energy cosmic rays above  $4 \times 10^{19}$  eV have repeatedly reported positive results [27, 28, 29, 30, 31, 32].

Searches for small-scale clustering usually involve the calculation of the two-point-correlation function: for a given set of cosmic ray events with energies above some threshold  $E_{th}$ , the number of pairs  $n_p$  separated by an angular distance less than  $\theta$  is counted and compared with the number expected in an isotropic distribution of arrival directions. This is used to calculate the chance probability  $P(E_{th}, \theta)$  of finding  $n_p$  or more pairs in a random data set just by chance. As an example, the published AGASA data set of 57 events with energies above  $4 \times 10^{19}$  eV recorded until May 2000 contains 4 doublets and 1 triplet, where a doublet is defined as two events with angular separation of less than  $2.5^\circ$ . As straightforward as this counting might sound, there is considerable disagreement over the statistical significance of this potential signal. In fact, the literature gives chance probabilities between  $10^{-4}$  and 0.2. Fig.1 shows an updated skymap with data taken until 2002, with doublets and triplets indicated.

The problem arises from the way the chance probability of the signal is evaluated. Several important parameters of the analysis are not determined *a priori*, among them the maximum angular separation of two events that defines a cluster, and the minimum energy of the showers used in the analysis. The optimal angular separation that defines a cluster is unknown as magnetic smearing might cause clustering to occur at angular scales somewhat larger than the angular resolution of the instrument. Unknown magnetic deflections also make the choice for the energy threshold difficult, because a higher energy threshold may reduce deflections of charged cosmic ray primaries by

magnetic fields, but it also weakens the statistical power of the data set.

Many authors have approached the problem by scanning the parameter space for angular separations, energy thresholds and - in the case of correlation searches - source catalogs that maximize a correlation. This is a legitimate approach, but it does not yield the significance of the potential signal. Once a potential clustering signal is found after scanning over one or more parameters, the probability that the null hypothesis (“the sky is isotropic”) is rejected needs to be evaluated with a statistically independent data set where the parameters that were found *a posteriori* to maximize the “signal” in the original data set are now treated as *a priori*. This is tough if the data set is small to begin with, and it is tempting to abandon this rigorous procedure in favor of more or less complete estimates of “penalty factors” resulting from the scan over the parameter space.

In the case of searches for small-scale clustering, this scan is usually performed over some range of separation angles  $\theta$  and energy thresholds  $E_{min}$  simultaneously. In the first step, the scan determines which energy threshold and angular separation maximized the clustering signal. Once found, the statistical significance is then evaluated by performing identical scans over many simulated isotropic data sets with the same exposure, and counting the sets that have a stronger signal somewhere in the parameter space.

Such scans have been performed for the AGASA data set [49], the HiRes stereo data set [50], and the Auger data set [51]. For the HiRes data set with 271 events above  $10^{19}$  eV, no significant clustering signal is found for any separation angle between  $0^\circ$  and  $5^\circ$  and any energy threshold above  $10^{19}$  eV. The same method gives a chance probability of  $3 \times 10^{-3}$  for the strongest AGASA clustering signal, above  $4.9 \times 10^{19}$  eV with  $\theta = 2.5^\circ$ . The Auger data (1 January 2004 - 15 March 2007) were scanned above a minimum energy of  $2 \times 10^{19}$  eV up to a maximum  $\theta$  of  $30^\circ$ . The most significant signal, at  $\theta = 7^\circ$  for  $E > 5.75 \times 10^{19}$  eV, has a chance probability of  $2 \times 10^{-2}$ .

Note that there are some hidden “penalty” factors that even this method cannot account for. Arrival direction data sets are analyzed for possible anisotropies of many kinds. Small-scale clustering is just one example of a deviation from isotropy that an observer might find interesting. Other examples include events forming line-like structures [52], or accumulating in particular regions of the sky, or aligning with the galactic plane or the supergalactic plane, or having a celestial dipole or quadrupole dependence, or correlating with positions of particular accreting neutron stars or black holes, or particular fast pulsars, or nearby supernova remnants, or colliding galaxies, or gamma ray bursts, etc. Astrophysical candidates can be targeted individually or “stacked” by targeting numerous ones collectively. Correlation with some catalog is an example of that. There is no rigorous way to count the types of anisotropy that are of potential interest. Any finite data set drawn from an isotropic distribution will have irregularities, and thorough exploration is likely to result in some intriguing patterns which occur very rarely in other data sets similarly sampled from isotropy. Without *a priori* specification of what to look for, it is impossible to know how many tests were applied in recognizing an intriguing pattern. The danger is that a search without a

pre-defined goal may overestimate the significance of a feature that is discovered by exploration.

The AGASA small-scale clustering signal, with a chance probability of  $3 \times 10^{-3}$  as mentioned above is a good example for the perils of estimating penalty factors. As shown in [49], the chance probability for small-scale clustering actually increases to almost 0.2 in an analysis that discards the data that were taken before the first published claim of a clustering signal [27] and tests the claim using only data taken afterwards. Similar problems with published claims of significant small-scale clustering have been pointed out by various authors [49, 53, 54].

At present, there is no confirmed evidence for significant clustering of cosmic ray arrival directions. Clearly, any clustering of arrival directions is weaker than previously suggested.

#### 4.3. Maximum Likelihood Ratio

While the two-point-correlation function has been widely used in cosmic ray data analysis, it has some shortcomings. It requires the choice of an energy threshold and, by simply scanning over angular separations, it assumes that the angular resolution of the experiment can be characterized by a single average value. In reality, the angular resolution of cosmic ray detectors is not a constant, but rather depends on a variety of parameters, most notably the energy and the position of the air shower relative to the detector. Energy-dependent magnetic deflections can also not be accounted for with a single rigid value for the angular resolution.

The application of maximum likelihood techniques is a way to overcome some of these shortcomings. As an example, a maximum likelihood ratio test that makes full use of the instrument's point spread function has been applied in searches for point-like sources in the combined HiRes and AGASA data set of cosmic rays with energies above  $4 \times 10^{19}$  eV [55], and in the search for correlation of arrival directions with objects of the BL Lacertae class of AGN [56]. The method can easily be extended, for example to allow for different source strengths in correlation studies [57].

In the search for cosmic ray point sources, the likelihood ratio  $\mathcal{L} = P(\text{Data}|\text{H}_1)/P(\text{Data}|\text{H}_0)$  is calculated for a given position  $\vec{x}$  on the sky. Here,  $P(\text{Data}|\text{H}_1)$  is the likelihood for the source hypothesis (“a source at position  $\vec{x}$  contributes  $n_s$  source events in addition to the expected background”) and  $P(\text{Data}|\text{H}_0)$  is the likelihood of the null hypothesis (“the event density at  $\vec{x}$  is due to background”). One can now maximize the likelihood ratio as a function of  $n_s$  to obtain the best estimate for the number of events contributed by a source at  $\vec{x}$ . This estimate can then be calculated for a dense grid of points on the sky covering the full range of equatorial coordinates  $\alpha$  (right ascension) and  $\delta$  (declination) accessible to the experiments. The parameters  $\alpha$ ,  $\delta$ , and  $n_s$  which maximize the likelihood ratio will therefore give us the best estimate for the position of a source and the number of events it contributes.

The calculation of  $\mathcal{L}$  utilizes the arrival direction accuracy for each event and the

background probability for each position on the sky. It therefore uses all available information for each event. Additional factors, for example the deflection of charged cosmic ray primaries in magnetic fields, can be included even if the magnetic fields that cause the deflection are poorly known. This can be done by treating the magnetic field strength as a nuisance parameter that is removed by marginalizing over all possible magnetic fields. The marginalized likelihood ratio automatically accounts for the statistical penalty from the consideration of many magnetic field models. Marginalized likelihood ratios are a common tool in many areas of parameter estimation, see for example [58].

The analysis of the combined HiRes and AGASA data above  $4 \times 10^{19}$  eV does not reveal evidence for a statistically significant point source of cosmic rays. The strongest “hot spot” is found to have a chance probability of 28 % to appear in a random isotropic data set [55].

In searches for correlations with known astrophysical objects, there are additional choices to be made in the selection of the classes of possible sources. Besides the choice of astrophysical objects, there are, for example, choices for the minimum magnitude or maximum distance of sources that are deemed likely candidates for correlations with cosmic rays. The search for correlations of ultrahigh energy cosmic rays with objects of the BL Lacertae class of AGN is an example of a search where the selection criteria were changed with each new analysis. Sources were first selected based on redshift ( $z > 0.1$  or unknown), optical magnitude ( $m < 18$ ), and 6 cm radio flux ( $F_6 > 0.17$  Jy) [34], then on optical magnitude alone ( $m < 18$ ) [35], then, in [36], on their possible association with gamma ray sources from the 3<sup>rd</sup> EGRET Catalog [59]. Each search resulted in significant claims, mainly based on data recorded by AGASA and the Yakutsk experiment, applying various energy cuts. Several authors have pointed out the dangers of this approach [54, 60], and statistically independent data sets subsequently did not confirm the correlations [61, 56].

A particular correlation first claimed in [62] based on the HiRes stereoscopic data set is not ruled out at this point. In this analysis, the 157 confirmed BL Lac objects with optical magnitude  $m < 18$  from the 10<sup>th</sup> Catalog of Quasars and Active Nuclei by Véron-Cetty and Véron [63], were found to show correlations with the arrival directions of the 271 cosmic rays with energy  $E > 10^{19}$  eV taken between December 1999 and January 2004. The correlation is analyzed in detail in [56], where the authors also point out that statistically independent data is necessary to estimate the significance of the correlation. Independent stereoscopic data taken after January 2004 did not confirm the correlation, but since the independent data set is smaller than the original and the HiRes experiment was discontinued in 2006, the correlation claim is not ruled out at a satisfying confidence level.

Data from the Pierre Auger Observatory was used to search for an equivalent signal in the southern hemisphere, and no correlation was found [64], but it has been pointed out that the smaller number of confirmed BL Lac objects in the southern sky requires a larger data set to confirm or disprove the correlation signal [65].

#### 4.4. Previous Claims: What could have gone wrong?

Cosmic ray anisotropy detections have been made by researchers in good faith, believing that they have uncovered essential clues to the origins of the mysterious high energy charged particles. Scientists are highly motivated to discover the sources, and they feel an obligation to report any clues that they find in the data. A person who toils for years to build a more powerful detector than any predecessor naturally does so in hopes of finding new clues. There is a strong psychological preference for a positive result as opposed to a null result.

After exploring a data set thoroughly, some intriguing pattern is likely to be found. There is a long list of potential objects and also many different classes of astrophysical objects that one might consider as sources. There are many possible signatures for autocorrelation. There are many large scale patterns to consider. For each kind of potential anisotropy, a thorough search would try all possible cuts on energy. For many of them, angular separation cuts would be varied. An unrestricted exploration of a data set entails a huge number of trials, and the effective number of trials cannot be estimated. When you look at a skymap, you will see a pattern that is there. But how many other patterns of equal or greater interest might you have found if they had been there? There is no way to count them.

Motivated by the desire to find new clues, it is natural to cite reasons why a discovered pattern is particularly interesting. It may seem that the observed pattern should have been one of the first things for which to look. In this *a posteriori* analysis, it is then natural to argue that the discovered pattern would have been found with very few trials since any sensible scientist would have looked for it with high priority. Similarly, one may find reasons why the energy cuts and angular cuts that maximize the “signal” are physically reasonable. They can seem like natural choices to make, so perhaps only a small statistical penalty (or no penalty at all) need be assessed for discovering the signal at its maximum significance.

Confidence that a signal is genuine can lead to overlooking other types of trials. In studying the behavior of the signal, one might find that it is enhanced by an alternative event reconstruction technique, by different reconstruction quality cuts, by different zenith angle cuts, by discarding (or including) certain epochs when the detector was irregular in some respect, etc. For optical detectors, maybe weather cuts or atmospheric quality cuts can be adjusted to enhance the signal. A stronger signal may be regarded as reason enough to accept such optimization of quality cuts as sensible, if one is certain that the signal is genuine. The quality cuts might be reported without mentioning that they were tuned to enhance the signal. Strong confidence that an apparent signal is genuine might come, for example, from a published model that calls for the discovered anisotropy or from corroborating results reported by another experiment (bandwagon effect).

The estimated statistical significance of anisotropy reported in *a posteriori* analyses should be viewed with skepticism. Confirmation of the anisotropy by clearly specified

procedures applied to independent data is essential.

#### 4.5. Results from the Pierre Auger Observatory

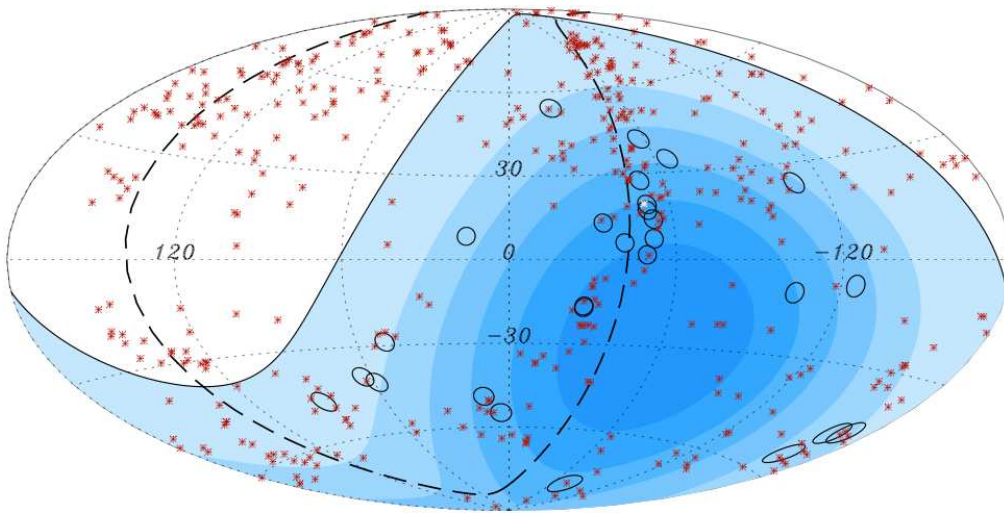
Recently, the Pierre Auger Observatory published first results of anisotropy studies based on data taken between January 2004 and August 2007 [11, 12]. The analysis shows evidence for a correlation between the arrival directions of cosmic rays with energies above  $6 \times 10^{19}$  eV and Active Galactic Nuclei with distances less than 75 Mpc taken from the 12<sup>th</sup> Catalog of Quasars and Active Nuclei by Véron-Cetty and Véron [66]. The analysis finds that the hypothesis of an isotropic arrival direction distribution of the highest energy cosmic rays is rejected at the 99 % confidence level.

To avoid the pitfalls of earlier analyses, the correlation search was performed in two steps. An exploratory analysis first identified the angular separation, energy threshold, and maximum AGN redshift that maximize the correlation signal. The data used to fine-tune the cut parameters were then discarded, and the correlation was tested on new independent data for which all cuts were considered *a priori*. The test was performed as a sequential analysis where the correlation signal is evaluated after each new event, and the test stopped after the null hypothesis (no correlation) was rejected at least at the 99 % confidence level.

At present, based on data taken between 1 January 2004 and 31 August 2007, the correlation signal has maximum strength for cosmic rays with energies greater than  $5.7 \times 10^{19}$  eV and AGN with redshift  $z \leq 0.017$ , with a maximum angular distance that defines a correlation of  $3.2^\circ$ . For these parameters, 20 out of 27 events correlate with the positions of AGN. As the data set is still small, these parameters merely give a first estimate of the relevant angular scale and energy threshold. Fig. 2 shows a skymap of the cosmic ray arrival directions and the positions of AGN with  $z \leq 0.017$ , together with the relative exposure of the Auger Observatory.

The Auger correlation signal shows that the cosmic ray sky at the highest energies is not isotropic and that charged particle astronomy at these energies is indeed possible. While a firm interpretation of the signal has to await additional data, the signal already shows some remarkable features. The energy threshold that maximizes the correlation signal coincides with the energy of the GZK suppression, defined here as the energy where the flux has dropped to 50 % compared to a simple power law extrapolation of the spectrum. This further supports the interpretation that the steepening of the spectrum at  $6 \times 10^{19}$  eV is indeed due to the GZK effect rather than an intrinsic feature of the source spectra. The angular scale of the correlation signal of  $3.2^\circ$  indicates that deflections in magnetic fields are small and the cosmic ray primaries are not predominantly heavy nuclei. At this point, however, it is unclear whether AGN are the sources or act merely as tracers of the true sources. The distribution of matter in the nearby Universe is not isotropic, and the distribution of the nearby AGN correlates with the matter distribution. Furthermore, the AGN catalog that forms the basis of this analysis is known to be incomplete, in particular near the galactic plane. While not





**Figure 2.** Skymap (in galactic coordinates) of arrival directions of cosmic rays with energies above  $5.7 \times 10^{19}$  eV recorded by the Pierre Auger Observatory, and positions of Active Galactic Nuclei with redshift  $z \leq 0.017$ . The cosmic ray events are shown as circles of radius  $3.2^\circ$  centered on the arrival direction, the AGN are shown as red asterisks. The blue shading indicates the relative exposure of the Observatory, with darker color indicating larger exposure. The dashed line indicates the supergalactic plane, and the position of Centarus A is marked by a white star. Taken from [12].

relevant for the statistical evaluation of the correlation signal, the incompleteness is an obstacle on the way towards an interpretation of the signal.

While the correlation signal is a first indication that most cosmic rays with energies above  $6 \times 10^{19}$  eV are protons from nearby AGN or sources with a similar spatial distribution, many questions remain open. With the small number of events, distinctive properties of the subset of AGN that correlate with cosmic rays cannot yet be identified. While two events come from within  $3^\circ$  of Centaurus A (at 3.4 Mpc distance one of the closest AGN), there are more distant AGN that lie in almost that same direction. Moreover, no event has been observed from the direction of the Virgo supercluster, which contains the giant elliptical galaxy M87 at a distance of only 18 Mpc.

The Pierre Auger Observatory is only at the very beginning of its life. The data used for the current analysis corresponds to roughly 1.2 years of operation of the complete detector. In little more than a year, the exposure will already have doubled. With more data, an unambiguous identification of the sources might be possible, and individual sources might start to emerge.

## 5. Ultrahigh Energy Gamma Rays and Neutrinos

In the previous chapter, we summarized the current status of astronomy with cosmic rays at ultrahigh energies. Cosmic rays are not the only messenger particles that potentially arrive from cosmic particle accelerators. If (charged) cosmic rays are accelerated in astrophysical objects like supernova remnants or AGN, high energy gamma rays and

neutrinos are secondary products of this acceleration. When high energy protons hit ambient gas and radiation in the vicinity of the acceleration sites, the production and subsequent decay of charged and neutral pions produces gamma rays and neutrinos. Gamma rays are also produced by bremsstrahlung and synchrotron losses, and inverse Compton scattering can upscatter photons to higher energies.

We will now discuss the possibility of astronomy with gamma rays and neutrinos at ultrahigh energies.

### 5.1. Gamma Rays

Galactic and extragalactic sources of gamma rays with energies up to tens of TeV have been identified with high statistical significance by air Cherenkov telescopes for several years now. Lately, several extended sources of gamma rays have been identified by the Milagro gamma ray allsky survey [67]. The gamma rays observed by these experiments are the highest energy particles seen that we can associate with discrete astrophysical sources.

At energies above several tens of TeV, the Universe is no longer transparent to gamma rays as they interact with extragalactic background photons. At 20 TeV, the mean free path of gamma rays on the infrared background is only about 100 Mpc, and above 100 TeV, interaction with the microwave background leads to an even more dramatic drop in the mean free path, down to about 10 kpc near  $10^{15}$  eV. At much higher energies, above  $10^{19}$  eV, the isotropic radio photons become the dominant background targets, but the attenuation length remains well below 100 Mpc, with some uncertainty due to our poor knowledge of the radio background.

The prospects for extragalactic gamma ray astronomy at energies above several tens of TeV are therefore dim. Nevertheless, there are many scenarios for cosmic ray production that predict a substantial fraction of gamma rays in the cosmic ray flux above  $10^{19}$  eV. Top-down models are an example. Partly created to address the problem that particle acceleration to energies above  $10^{20}$  eV by electromagnetic processes is difficult in known astrophysical sources, these models also offer an explanation for the observed isotropy of arrival directions and the extension of the spectrum beyond GZK energies as seen by AGASA. Rather than assume a “bottom-up” acceleration, top-down models assume that ultrahigh energy cosmic rays are the decay products of supermassive particles, so-called  $X$  particles, that can have masses up to  $10^{24}$  eV. Examples are magnetic monopoles and other topological defects that might have been produced in the early stages of the Universe; see [68] for a review of these models.  $X$  particles decay into quark-antiquark pairs, producing two jets with about 95 % pions and 5 % baryons. The majority of ultrahigh energy particles detected on Earth should consequently be photons from pion decay.

Another model that predicts photon primaries is the Z-burst model [69], which is an attempt to explain the ultrahigh energy cosmic ray flux and its features without the need for acceleration. The model is based on the idea that ultrahigh energy

cosmic ray neutrinos interact with the relic neutrino background, generating  $Z$  bosons that immediately decay with photons of ultrahigh energy as the main decay product. The theoretical motivation for some of these models has waned with the accumulating evidence for the GZK cutoff.

Up to recently, upper limits on the fraction of photons in the cosmic ray flux did not impose serious constraints on top-down models or the Z-burst scenario. Data from the Haverah Park experiment were used to set upper limits on the photon fraction of 48 % above 10 EeV and 50 % above 40 EeV [70, 71], and AGASA data were used to set upper limits of 28 % above 10 EeV, 67 % above 32 EeV [72], and 67 % above 125 EeV [73] (all limits at 95 % c.l.).

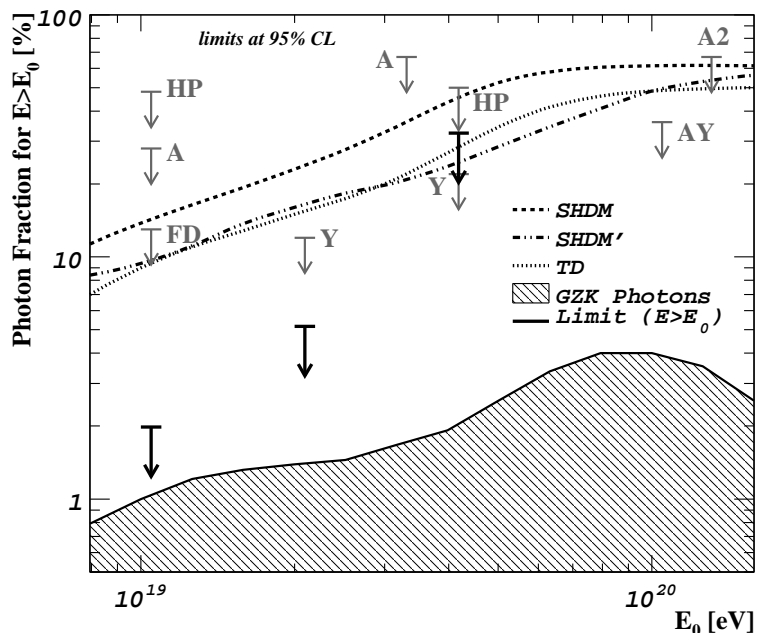
The situation has changed with the influx of data from the Pierre Auger Observatory. New upper limits have now been reported from fluorescence detector and surface detector data [21, 23] based on measurements of the height of the shower maximum. On average, the depth of shower maximum for 10 EeV photons is  $1000 \text{ g cm}^{-2}$  as compared to  $800 \text{ g cm}^{-2}$  for protons of the same energy. At energies above about 10 EeV, the Landau-Pomeranchuk-Migdal (LPM) effect [76, 77], a suppression of the Bethe-Heitler cross section, further delays the shower development. In addition, above about 50 EeV, the primary photon can interact with the geomagnetic field and convert to  $e^+e^-$ -pairs which subsequently create more photons via bremsstrahlung, initiating a pre-shower of particles above the atmosphere. What ultimately enters the atmosphere is not a single photon, but several low energy particles. This effect, which strongly depends on the energy and incoming direction of the primary gamma ray relative to the local geomagnetic field, can counteract the delay of the shower development due to the LPM effect, and both effects need to be taken into account when simulating photon primaries.

The air fluorescence detectors of the Pierre Auger Observatory determine the depth of shower maximum directly. For the surface detector data, several observables indirectly indicate the height of the shower maximum, and the data taken in hybrid mode allow for a careful cross-check of both direct and indirect techniques.

With hybrid data, an upper limit of 16 % for the photon fraction in the cosmic ray flux above  $10^{19} \text{ eV}$  was obtained at 95 % confidence level [21]. The larger data set taken with the surface detector array alone yielded upper limits of 2.0 %, 5.1 %, and 31 % at  $10^{19} \text{ eV}$ ,  $2 \times 10^{19} \text{ eV}$ , and  $4 \times 10^{19} \text{ eV}$ , respectively [23]. Fig. 3 shows these limits along with limits from previous experiments, predictions from top-down models, and predictions for the flux of photons produced through photoproduction of pions in the interaction of cosmic rays with the microwave background (“GZK photons”).

## 5.2. Cosmogenic Neutrinos

Neutrinos are not only produced in the cosmic ray sources themselves, but also during cosmic ray propagation. Cosmic rays lose energy by photoproduction of mesons on extragalactic photons, and neutrinos are an end product of meson decay. The same



**Figure 3.** 95 % confidence limit upper limits on the fraction of photons in the integral cosmic ray flux, as a function of energy, from data taken with the surface detector array of the Pierre Auger Observatory [23] (black arrows). For comparison, the plot also shows previous experimental limits, from Haverah Park (HP) [70], AGASA (A1, A2) [72, 73], AGASA-Yakutsk (AY) [74], Yakutsk (Y) [75], and Auger hybrid data (FD) [21]. Predictions from top-down models and predictions of the GZK photon flux are also shown. Taken from [23].

interaction that is responsible for the GZK cutoff in the energy spectrum of ultrahigh energy cosmic rays therefore inevitably produces a diffuse flux of neutrinos at ultrahigh energies [78, 79]. Detecting these “GZK neutrinos” is the goal of several ongoing and planned experiments.

It is important to note that the neutrino cross section grows with energy, and at ultrahigh energies, neutrinos can no longer penetrate the Earth. Detecting upward-going muons, a technique applied at lower neutrino energies, therefore no longer works for ultrahigh energy neutrinos at  $10^{18}$  eV. The detection of a neutrino at such high energies is only possible if the neutrino interacts in close proximity to the detector producing an electromagnetic cascade. The challenge is to find ways to pick up this cascade with a detection technique that allows to probe very large volumes without the need to densely instrument the volume.

Experiments have recently started to use a detection technique that was suggested as early as 1962 by G. Askaryan [80, 81]. The electromagnetic cascade that develops after the neutrino interaction is not entirely symmetric in charge, as electrons and positrons have different scattering properties and interactions. The net excess of electrons over positrons means that the shower as a whole resembles a negative charge moving at nearly

the speed of light, producing Cherenkov radiation as a consequence. At wavelengths larger than the extent of the showers themselves, the emission is coherent; for a typical solid medium, the emission is coherent at radio wavelengths. It is crucial that the medium in which the radio emission is produced does not attenuate the radio signal appreciably. Ice is a suitable material, and several ongoing and future experiments use the Antarctic ice as the detector medium.

### 5.3. Detection of GZK Neutrinos

A dedicated instrument to study the cosmogenic neutrino flux is the Antarctic Impulsive Transient Antenna (ANITA) experiment [82]. ANITA detects neutrinos interacting in the Antarctic ice sheet by their coherent radio signal via the Askaryan effect described above. With an attenuation length of more than a kilometer, the ice is practically transparent for radio waves, and the radio pulses from the cascade can be picked up by antennas probing the ice surface from a balloon at an altitude of about 37 km. With this technique, about  $2 \times 10^6 \text{ km}^3$  of volume can be probed instantaneously, basically the entire visible area of the ice sheet up to a depth of about one attenuation length. The existence of the Askaryan effect in ice was confirmed in laboratory experiments before the first launch [83].

While the full instrument was first launched in December 2006, a smaller prototype, ANITA-lite, completed a successful 18.4 day flight in 2004. The upper limit at 90% confidence level on the flux  $F$  of cosmogenic neutrinos,  $E_\nu^2 \cdot F \leq 1.6 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  for energies  $10^{18.5} \text{ eV} \leq E \leq 10^{23.4} \text{ eV}$ , based on this data set [84] excludes several “exotic” models of ultrahigh energy cosmic ray production, most notably the Z-burst model, and improves considerably on the limits achieved with earlier experiments like GLUE [85] and FORTE [86]. With the full instrument, ANITA is expected to observe 5 to 50 GZK neutrinos for 50 days of flight time, bringing the sensitivity to the level where a detection of the cosmogenic neutrino flux is expected.

The observation time constraints imposed by the limited duration of balloon flights can be overcome by placing radio detectors in suitable configurations on the ground. The recently proposed Antarctic Ross Iceshelf Antenna Neutrino Array (ARIANNA) [87] plans to exploit the unique features of the Ross Ice Shelf near the Antarctic coast to increase the sensitivity for the detection of GZK neutrinos by an order of magnitude over ANITA. In its current design, ARIANNA consists of  $100 \times 100$  antennas on a square grid with 300 m spacing. Buried just under the surface, the antennas can detect direct radio emission from (nearly horizontal) neutrinos interacting in the shelf, or radio emission from downward-going neutrinos that is reflected at the water-ice boundary below the shelf. The thickness of the shelf is about 500 m. First estimates of the sensitivity of the instrument show that ARIANNA reaches down in energies to almost  $10^{17} \text{ eV}$ , bridging the energy gap between IceCube and ANITA.

#### 5.4. Pierre Auger Observatory as a Neutrino Detector

While primarily a cosmic ray detector, the Pierre Auger Observatory is also sensitive to neutrinos at EeV energies and above [88, 24, 90], the energy range relevant for the search for GZK neutrinos. If a  $\tau$ -neutrino interacts in the mountains or the ground near the Observatory, the  $\tau$  lepton is expected to travel tens of kilometers before decaying and producing an air shower. Because of the Earth's opacity to EeV neutrinos, such  $\tau$ -induced showers are nearly horizontal and can be detected readily above the Auger array. The showers caused by neutrino interactions differ markedly from very inclined showers caused by cosmic ray nuclei. A cosmic ray air shower at large zenith angle reaches ground level at a very large slant depth. The electromagnetic component is extinguished and only the muonic component survives. These showers are referred to as “old” showers. A “young” shower due to  $\tau$  decay is largely electromagnetic. The young electromagnetic shower produces signals in the tanks that are of relatively long duration. Since the signal in the surface detector tanks is read out by flash-analog-to-digital-converters (FADCs), narrow signals from cosmic ray showers and broad signals from earth-skimming  $\nu_\tau$  can be distinguished. The calculation of the detector acceptance for  $\nu_\tau$  is tricky. Only neutrinos from a small fraction of the sky, essentially nearly horizontal showers, can trigger the detector, and the interaction in the Earth has to occur at a distance from the detector that allows the  $\tau$ -decay air shower to develop above the array where it can be measured. Computer simulations give an acceptance of several times  $10^{16} \text{ cm}^2 \text{ s sr}$  above  $10^{19} \text{ eV}$ , with large systematic uncertainties from the  $\nu$  cross sections and the fact that the actual topography of the site is only included to some approximation. In the data set taken since January 2004, no earth-skimming  $\nu_\tau$ -event is seen, and a 90 % confidence level upper limit of  $E_\nu^2 \cdot dN_\nu/dE_\nu \leq 2.0 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  is set [24]. It should be noted that this limit is based on the  $\nu_\tau$  cross section from [89]. Since no measurement exists at these energies, the systematic error on the cross section is large, and the limit does not account for possible large deviations from the value in [89]. The limit is still well above theoretical expectations for the GZK neutrino flux, but is expected to improve by an order of magnitude over the lifetime of the Observatory.

In addition to earth-skimming  $\nu_\tau$ , there is also some sensitivity to downward-going neutrinos of all flavors. Again, at large zenith angles, these neutrino-induced showers can be distinguished from cosmic ray air showers by their electromagnetic component which appears as a broad signal in time in the FADCs. A search for down-going showers initiated by neutrinos and a study of the detector sensitivity for this component is ongoing [90].

## 6. Full-sky observatories

Cosmic ray astronomy must cover the entire sky. High energy cosmic ray experiments have historically focused on the energy spectrum and the chemical composition, and most detectors have been built in the northern hemisphere. Those include Volcano

Ranch, Haverah Park, Yakutsk, Akeno and AGASA, Fly's Eye and HiRes. Before the Auger Observatory, SUGAR (in Australia) was the only array to study cosmic rays at the highest energies in the southern hemisphere. Now the Auger Observatory site in Argentina has surpassed the cumulative exposure of the northern detectors, and over the next few years it will accumulate a data set which exceeds previous experiments by more than an order of magnitude. The southern sky has become over-observed relative to the northern sky.

The Auger Observatory was designed to have sites in both hemispheres in order to have nearly uniform coverage over the celestial sphere. The Auger plan is still to construct a site in southeast Colorado. If it is substantially larger than the Argentina site, then the northern exposure could catch up to the southern.

For cosmic rays above  $10^{19}$  eV it is possible to achieve a huge aperture by looking down on the atmosphere with a fluorescence detector satellite in space. The idea was first proposed by Linsley [91] and developed later by the OWL Collaboration [92] and EUSO [93]. The concept is now being developed most strongly as JEM-EUSO [94]. An orbiting satellite looks at showers in the northern and southern hemispheres equally, and it should achieve nearly uniform exposure to the celestial sphere.

Full-sky exposure is important for a variety of reasons:

- The cosmic ray source giving the greatest flux at Earth could be in any part of the sky. It is obviously advantageous to have a cosmic ray observatory well positioned to measure particles arriving from the brightest source.
- If no sources are to be detected, it is valuable to have uniform flux limits over the sky.
- If discrete sources are detectable, making an unbiased catalog of them requires good exposure to the full sky.
- Whether or not discrete sources are detected, it is important to measure whatever other anisotropy is present. Mapping the sky in various energy bins would provide invaluable constraints on theories about the sources and propagation of the cosmic rays through magnetic fields.
- Celestial scatter plots have intuitive meaning only if the exposure is approximately uniform. A steep exposure gradient makes it impossible to assess density patterns of arrival directions.
- Similarly, mapping the smoothed density function is unsatisfying if the density of arrivals is mostly tracking the exposure function. Plotting the statistical significance of density excess is a way to look for discrete sources, albeit with greatly different sensitivity in parts of the sky that differ greatly in exposure. Such a map does not help in evaluating large scale anisotropy.
- Multipole moments (the coefficients in a spherical harmonic expansion of anisotropy) are the natural way to characterize a celestial anisotropy. The celestial intensity function can be fully specified by a table of coefficients up to the order ( $l$ ) for which any structure would be smaller than the detector's angular resolution. Measuring the multipole moments does not require uniform exposure, but it does require full-sky coverage (see [95] for details). Each multipole is a  $Y_{lm}$ -weighted integral of the cosmic ray intensity

over the sphere of arrival directions. If there is a patch of the celestial sphere with undetermined intensity, then none of the multipoles can be measured. Assumptions must be made about the behavior in the missing patch in order to make even an unbiased estimate of any multipole. With full-sky coverage, the anisotropy can be measured unambiguously and characterized in a way that can be readily used to test theories.

- The angular power spectrum is a coordinate-independent measure of the amount of anisotropy on angular scales of  $1/l$  radians. The “power”  $C_l$  is simply the average squared multipole at order  $l$ . An unambiguous measure of the angular power spectrum requires exposure to the entire sphere of arrival directions.
- For large-scale patterns, the dipole and quadrupole moments may be the most important contributors. It is clearly not possible to measure these moments if a quarter of the sky is not exposed at all. In that case, observers are sometimes forced to find the dipole which best fits the intensity measured over the exposed part of the sky, *assuming the pattern to be a pure dipole*. If a quadrupole pattern is suspected (e.g. an excess from galactic equatorial regions), then the data might be tested against that hypothesis. In fact, with a detector in only one hemisphere, it can be difficult to distinguish a pure quadrupole from a pure dipole [96]. Without full-sky coverage, the search for large-scale anisotropy reduces essentially to hypothesis testing or to fitting a prescribed functional form. *Measuring* the celestial anisotropy requires exposure to the full sky. The full power of spherical harmonic expansion of the celestial intensity function is then available to characterize the anisotropy.

## 7. Summary

Cosmic ray astronomy is ultimately the study of individual cosmic ray sources via the particles that come from them. It should also be possible to infer properties of the intervening magnetic fields. The best hope for studying discrete sources this way is at the highest cosmic ray energies, even though the fluxes there are minuscule. It requires enormous exposure to acquire adequate statistics at extremely high energy, but there are reasons why this kind of astronomy may be plausible there. First of all, one can take advantage of the GZK effect to eliminate the isotropic background caused by sources throughout the distant Universe. The GZK distance limit restricts arrival directions to foreground sources in our part of the Universe. Secondly, protons near and above the GZK energy threshold have sufficient magnetic rigidity to penetrate through the galactic magnetic fields without being deflected more than a couple of degrees. Although the magnitude and coherence of intergalactic fields are poorly known, such high energy protons would probably not be deflected more than a few degrees coming from any source within that GZK radius. Together, these two reasons motivate a search for discrete sources at energies above the GZK energy threshold.

There is no guarantee that cosmic rays are produced by discrete sources. It is conceivable that they originate diffusely throughout the Universe. Top-down scenarios of cosmic ray production by decay or annihilation of super-heavy relic particles have been



a prominent possibility for diffuse cosmic ray production. Those models are constrained by the diffuse gamma ray intensity measured near 100 MeV. Top-down models that explain all the high energy cosmic rays would normally predict a higher-than-measured gamma ray background. The top-down models have recently been almost ruled out by new upper limits on the photon component of cosmic rays near  $10^{19}$  eV. Again, top-down models would normally exceed those limits. In principle, the density of high energy neutrinos can also be used to test for top-down production, since pion decays produce neutrinos as well as gamma rays. In practice, however, neutrino upper limits are much weaker than the gamma ray limits. The new gamma ray limits and evidence for the GZK suppression [6, 7] in the cosmic ray spectrum, are reasons to believe that cosmic rays are produced by a bottom-up acceleration process in special astrophysical sources. This is not a guarantee, but a strong suggestion, that discrete sources of cosmic rays are responsible for the particles that are recorded at Earth.

The fact that no individual source has so far been detected means that cosmic ray astronomy is not easy and might require much greater exposure. It is easier to detect the existence of discrete sources statistically than individually. One way is through autocorrelation of arrival directions. Significant clustering of arrival directions might be the first evidence for discrete sources. Alternatively, a correlation of arrival directions with a candidate set of astrophysical objects would also demonstrate anisotropy indicative of discrete sources. A correlation of that type can occur without any clustering of arrival directions, since it does not require having more than a single arrival direction from any one of the candidate sources. Data taken with the Pierre Auger Observatory indeed show first evidence of cosmic ray anisotropy at ultrahigh energies. The arrival directions of cosmic rays with energies above  $5.7 \times 10^{19}$  eV correlate with the positions of nearby ( $z \leq 0.017$ ) Active Galactic Nuclei.

The Pierre Auger Southern Observatory is nearing completion in Argentina, and its cumulative exposure is growing rapidly and is already large compared to that of any previous experiment. Constructing a larger Auger Northern Observatory in Colorado could soon provide exposure to the full sky. That would allow the detection of discrete sources with nearly uniform sensitivity over the full celestial sphere. Spherical harmonics could completely characterize the large-scale anisotropy. Although presently still only a hope, the prospects for cosmic ray astronomy are bright.

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